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FREE FALL AND EVAPORATION OF JP-4 JET FUEL
DROPLETS IN A QUIET ATMOSPHERE

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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SUMMARY

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In connection with the problem of the dispersion of jet fuel jet-tisoned at altitude, an analytical investigation has been made of free fall with and without evaporation in a quiet atmosphere of JP-4 fuel droplets of average composition. The significant physical characteristics (vapor pressure, etc.) of the droplets were approximated by replacing the chemically complex fuel by a mixture of ten petroleum "fractions" having predictable evaporation rates.

Results were obtained for most of the combinations of the following: initial droplet diameter: 250, 500, 750, 1000, 1500, and 2000 microns; initial altitude: 7000, 5000, and 3000 feet; and sea-level temperature: -30° , -15° , 0° , 15° , and 30° C. Calculations were also made for a few additional combinations involving droplets of 125-micron diameter and temperatures higher and lower than those mentioned.

As in a previous study (NACA RM E52L23a) of the free fall and evaporation of aviation gasoline droplets, it was found that temperature was the principal controlling variable; initial evaporation rates increased by factors of 15 or more as sea-level temperature increased from -30° to 30° C. Variations of initial altitude affected mass losses by only a few percent.

For example, initially large (2000 micron) droplets will have lost between 60 and 80 percent of original mass on striking the ground from initial altitudes between 3000 and 7000 feet for sea-level temperatures of 30° C, while the losses become insignificant (several percent) at sea-level temperatures of -30° C. An initially small (250 micron) droplet will have lost so large a fraction of its original mass after a fall of about several hundred feet at a high ground temperature that if it has not already reached the ground it probably never will. At low (-30° C) sea-level temperatures, the losses for 250-micron droplets are about 40 to 50 percent during a fall of 2000 feet, whereas the loss is only 20 percent for a 500-micron droplet.

It was concluded that the percentage of original mass lost by evaporation would, in general, be much less (after the first 15 or 20 percent) than in the case of a fall of gasoline under identical conditions. The residual mass percentage would be, however, critically dependent on air temperature and, to a lesser extent, upon the original distribution of droplet sizes.

INTRODUCTION

Frequently circumstances arise under which it becomes necessary to jettison all or a major fraction of the fuel load of an airplane. It should be possible to estimate the concentrations of liquid and of vaporized fuel at any given point in the atmosphere as a function of the dumping history and the elapsed time since the initiation of the dumping process.

A general solution would take into account the motion of the airplane during the jettisoning, the details of the dispersion process in the vicinity of the exit nozzles or ports, the effects of vehicle wake, the mean state of the atmosphere in the area, wind speeds and direction (particularly as varying with altitude), and intensities and scales of atmospheric turbulence (inclusive of local air currents). Clearly, a completely general solution is merely a goal.

In the present report, a theoretical treatment is presented of fall with and without evaporation of droplets falling freely through a quiet atmosphere. The details of the method are given in appendixes B and C. (Symbols are defined in appendix A.) The major basic assumptions are, however, discussed here briefly:

(1) Each droplet falls as though no other droplets are present. It is possible to show that the theoretical falling speeds are thus, particularly initially, too low. The calculated evaporation rates, on the other hand, are too great, but only trivially so.

(2) Evaporated molecules are immediately removed from the vicinity. In the absence of other droplets, this is essentially correct. In the presence of a sufficient concentration of nearby droplets, on the other hand, the rate of evaporation is overestimated under this assumption. Because of vertical dispersion of droplets of varying diameter, however, this effect cannot be a major one after several seconds of fall unless the range of droplet sizes is very small.

(3) Each droplet falls at all times at the terminal speed corresponding to its momentary diameter and the ambient conditions. In reality, the falling speed will be different from terminal by a small amount which varies with size, rate of evaporation, and so forth (ref. 2).

(4) Droplet temperature is uniform and identical with ambient temperature. This assumption implies that the evaporation rate is determined solely by the mass-transfer rate and not at all by the heat-transfer rate. This is, of course, not strictly correct; JP-4 droplet cooling varies between a fraction of a degree and 4° or 5° C. Speed of execution of the calculations was, however, greatly increased as a result of this simplification and, except at the combination of high air temperatures and small droplet sizes, the results were not significantly affected.

(5) It is possible to simulate the evaporative behavior of a very complex fuel by replacing it for computational purposes by a suitable mixture of a reasonable number (in this work, ten) of components having definite boiling points and other physical and chemical properties.

It happens that the sense of the error in the calculated evaporation rates is the same for the first four of the assumptions. (The sense of the error is not readily determinable in the case of the last assumption.) The cumulative effect of all the assumptions, however, remains well below any reasonable estimate of the maximum probable deviation of the results from actual evaporation rates, namely, ± 20 percent. The uncertainty of the composition of a given sample of fuel would, alone, imply an average uncertainty in evaporation rate of about ± 10 percent.

RESULTS AND DISCUSSION

The results of the calculations described in appendixes B and C are exhibited in several figures and discussed in the present section.

In figure 1 the speed of fall of a droplet of JP-4 is indicated as a function of droplet diameter at an altitude of 1000 feet under standard (NACA atmosphere; sea-level temperature, 15° C) conditions. The assumption here is that no evaporation is occurring, which is essentially correct at air temperatures (at altitude) below -30° C (for JP-4). It is seen that falling speeds approach 20 feet per second for droplets of 2000-micron diameter but decrease to 2 feet per second at 200 microns and become vanishingly small for engineering purposes below 25 microns.

Falling speeds increase slowly, and Reynolds numbers decrease, with altitude. Such changes are shown clearly in figure 1 of reference 1 for gasoline and are not repeated here. (The effect of air temperature changes was estimated; it was negligible for engineering purposes.)

The altitude-time histories of droplets of 250-, 500-, 750-, 1000-, 1500-, and 2000-micron diameter falling from altitudes of 3000, 5000, and 7000 feet at sea-level temperatures of -30°, 0°, and 30° C are shown

in figure 2. The curves of this figure reflect only decreases in falling speed attendant upon the evaporative decreases of droplet diameter and mass; altitude effects are considered only insofar as evaporation rates are concerned (appendix C). At the larger droplet diameters, perhaps above 1000 microns, the magnitude of the decrease of distance of fall with a given increase of sea-level temperature is not great. However, the effect increases rapidly with decreasing diameter.

For example, the effect in the case of a 2000-micron droplet is small; for a 500-micron droplet, however, a temperature change from -30°C to 30°C reduces the distance the droplet falls in 3 minutes from 1060 to 600 feet (estimated) for a starting altitude of 5000 feet.

The effect of air temperature changes on droplet fall is exhibited more directly in figure 3. The distance of fall for two periods of fall is given for droplet diameters of 500, 1000, and 1500 microns. At the end of a 100-second interval, under the conditions stated in the figure, relatively little change of distance of fall occurs over the sea-level temperature range of -30° to 30°C despite the initial evaporative losses that occur at the 30°C temperature. However, at 300 seconds the distance of fall varies markedly with temperature; this is indicative of the marked evaporative losses that occur at the higher temperatures over the longer period.

In figure 4, the ratio of the mass of a JP-4 droplet to the original mass is given as a function of distance of fall for initial altitudes of 3000, 5000, and 7000 feet, sea-level air temperatures of -30° , -15° , 0° , 15° , and 30°C , and droplet diameters of 250, 500, 750, 1000, 1500, and 2000 microns.

Certain limitations of the combination of digital computer and program prevented completion of a number of the runs involving small droplets. However, in most such cases, residual masses were small when the runs came to an end.

A few numerical examples of fractional mass losses through evaporation as presented in figure 4 are given in the following list:

Distance of fall, ft	Droplet diameter, microns	Sea-level air temperature, $^{\circ}\text{C}$			
		-30	0	15	30
1000	250	0.33	0.94	^a 0.99	>0.99
	500	.15	.51	.76	^a .95
	1000	.05	.27	.45	.67
	2000	.015	.13	.24	.40
3000	250	^a 0.050	^a 0.99	>0.99	>0.99
	500	.27	^a .74	^a .90	^a >.99
	1000	.13	.46	.68	^a .85
	2000	.05	.25	.43	.64

^aEstimated.

In general, mass loss rates are high for small (250-500 micron) droplets at sea-level temperatures above 15°C and moderate at sea-level temperatures from 0° to 15°C . Below 0°C , mass loss rates are small but must be considered even in approximate calculations at the smaller droplet sizes. For droplets larger than 1250 microns, mass loss rates may be neglected below 0°C for many engineering purposes. Mass loss rates for such droplets are low at sea-level temperatures between 0° and about 10°C , moderate from 10° to about 20°C , and high at higher temperatures, though of course smaller than those of the smaller droplets.

The effect of air temperature changes on droplet mass loss rates is indicated more directly by figure 5. The residual mass ratio is given in the figure as a function of sea-level air temperature for two distances of fall and for three original droplet diameters. The starting altitude is 5000 feet. The very great rate of increase with temperature of the mass loss rate of 500-micron droplets is obvious even in the case of a 500-foot fall. The effect is less pronounced at the larger diameters, but even a 1000-micron droplet loses more than 20 percent of its mass during a 1000-foot fall at air temperatures (at altitude) above -20°C , corresponding to sea-level air temperatures higher than -10°C .

Lewis Research Center

National Aeronautics and Space Administration

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APPENDIX A

SYMBOLS

(Quantity nondimensional if units not given.)

$^{\circ}\text{API}$	measure of specific gravity, $\left(\frac{141.5}{\text{specific gravity}} - 131.5\right)$
C	constant, $(^{\circ}\text{K})^{-1}$
C_D	drag coefficient
C_1, C_2	constants of vapor pressure relation (eq. (C10)) (complex units)
D	diameter, cm
D_{μ}	diameter, microns
g	gravitational force, dyne g^{-1}
H	altitude, ft
$h_{m,i}$	mass-transfer coefficient for i^{th} component, $(\text{g/sec cm}^2)/(\text{dyne/cm}^2)$
L_v	heat of vaporization, erg g^{-1} (unless other units specified)
M	molecular weight, g mole $^{-1}$
M_i	molecular weight of i^{th} component, g mole $^{-1}$
m_d	mass of droplet, g
m_i	mass of i^{th} component, g
NBP	normal boiling point, $^{\circ}\text{R}$
NP	normal pressure (1,013,250), dyne cm^{-2}
NT	normal temperature, 491.7°R or 273.16°K depending upon equation
Nu_m	Nusselt number for mass transfer
n	exponent of temperature factor in expression yielding β_1 , taken as 1.75 in these calculations
P	pressure, dyne cm^{-2} (unless other units specified)

P_i	vapor pressure of i^{th} component when not mixed with other liquids, dyne cm^{-2} (unless other units specified)
R	universal gas constant, erg mole $^{-1}$ $^{\circ}\text{K}^{-1}$
Re_t	Reynolds number of droplet motion at terminal falling speed
r	droplet radius, cm
Sc	Schmidt number, $\mu_a/\beta\rho_a$
T	temperature, $^{\circ}\text{K}$
T^*	temperature, $^{\circ}\text{R}$
t	temperature, $^{\circ}\text{C}$
U_t	terminal speed of fall of droplet, feet sec $^{-1}$
V_a	characteristic volume of air, 28.966/0.92, cm^3 mole $^{-1}$
V_i	mole-volume of i^{th} substance, cm^3 mole $^{-1}$
v_i	partial volume of i^{th} component (on hypothetical basis of isolation of components from one another), m_i/ρ_i , cm^3
α_d	total number of moles of fuel in droplet, $\sum_{i=1}^{10} \alpha_i$, mole
α_i	moles of i^{th} component, m_i/M_i , mole
β	mass diffusivity, cm^2 sec $^{-1}$
ϵ_i	mole fraction of i^{th} component, α_i/α_d
θ	time, sec
μ	viscosity, poise
ρ	density, g cm^{-3}
ρ_d	droplet density, g cm^{-3}
ρ_i	component density (as though isolated), g cm^{-3}

φ see eq. (B1)

Subscripts:

a air

d droplet

i i^{th} component

ref reference value

t terminal

μ in micron units

O standard conditions (generally, 1-atm pressure and temperature of 0° C; NACA standard temperature, 15° C)

APPENDIX B

FREE FALL OF DROPLETS IN ATMOSPHERE

A digital computer program was written and executed which had as a primary goal the determination of no-evaporation falling histories (altitude as a function of time, etc.) of spheres having densities and sizes corresponding with those of jet fuel droplets. A secondary goal was the determination of the extent to which it was actually necessary in computer programs to take into account altitude and temperature effects on falling speeds of such droplets (again, apart from evaporation).

The following relations were used in the no-evaporation, free-fall calculations; they are explained below:

$$\phi \equiv \frac{32}{3} \frac{\rho_d \rho_a g r^3}{\mu_a^2} = C_D Re_t^2 = f(Re_t) \quad (B1)$$

$$Re_t \equiv \frac{2\rho_a r U_t}{\mu_a} \quad (B2)$$

$$Re_t = 10 \left[-1.35134 + 1.02468 \log_{10} \phi - 0.046399 (\log_{10} \phi)^2 \right] \quad (B3)$$

$$U_t = 10 \left[-5.3010314 + 3.4916319 \log_{10} D_\mu - 0.45934595 (\log_{10} D_\mu)^2 \right] \quad (B4)$$

$$Re_t = 10 \left[-6.9751797 + 4.4711509 \log_{10} D_\mu - 0.45358085 (\log_{10} D_\mu)^2 \right] \quad (B5)$$

$$U_t = 10 \left[-5.1028364 + 3.3115722 \log_{10} D_\mu - 0.41884542 (\log_{10} D_\mu)^2 \right] \quad (B6)$$

$$Re_t = 10 \left[-6.6574989 + 4.2189919 \log_{10} D_\mu - 0.40335337 (\log_{10} D_\mu)^2 \right] \quad (B7)$$

$$\rho_d = 0.78504 - 0.000774 t_d \quad (B8)$$

$$\rho_a = (0.20693671 - 1.4227617 \times 10^{-6} H)^{4.2561} \quad (B9)$$

(where H is in feet even though the air density ρ_a is in cgs units)

$$\mu_a = 1.718 \times 10^{-4} + 5.08 \times 10^{-7} t_a - 4.93 \times 10^{-10} t_a^2 \quad (B10)$$

$$t_a = 15 - 0.0019812 H \quad (B11)$$

$$t_d = t_a \quad (B12)$$

It was pointed out in reference 1 that G. C. Williams of M.I.T. had provided (ref. 3) a simple means of calculation of the terminal falling speed of a sphere in a fluid.

Williams had shown that a nondimensional function ϕ may be defined (eq. (B1)) which is simply related to drag coefficient C_D and the terminal Reynolds number Re_t of a falling sphere; the Reynolds number is calculated as indicated in equation (B2). In equation (B1), $f(Re_t)$ is an experimentally determined function.

The procedure required to determine U_t is then to calculate ϕ by using equation (B1), Re_t by using the experimentally determined relation between Re_t and ϕ , and, finally, U_t by using equation (B2).

A cursory investigation indicated that for Re_t greater than unity a single expression (eq. (B3)) connecting ϕ and Re_t would fit the data published in Williams' dissertation (ref. 3), in which he summarized experimental results in this field.

At Reynolds numbers less than unity, Stokes law applies, which in the present notation may be expressed either as $Re_t = \phi/24$ or $C_D = 24/Re_t$.

The calculations were programmed on a time-step basis; at the beginning of a step the mean air properties and so forth were estimated for that step using a simple extrapolation technique. The mean falling speed and distance of fall were then calculated; if necessary, estimated mean air properties, and so forth, were revised and the calculation was repeated.

Results were obtained for a range of starting altitudes from 1000 feet above sea level to 10,000 feet and for a range of droplet diameters from several microns to several thousand.

Upon analysis, it was found that for altitudes between sea level and about 7000 feet the net effect of variations of density and viscosity on falling speeds was of the order of a few percent. It was, in fact, concluded that if calculations of histories of evaporating droplets are to be performed on a slow- or even medium-speed computer, it is desirable to ignore altitude effects on falling speeds (at low altitudes).

The approximate relations arrived at are given as equations (B4) and (B5) for droplet diameters up to and including 200 microns, and (B6) and (B7) for droplets having diameters greater than 200 microns.

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Relations (B4) to (B7) provide approximately correct terminal falling speeds and Reynolds numbers at low altitudes as a function of droplet diameter alone for droplets having densities near 0.8 g cm^{-3} and diameters from several microns to about 3000. The maximum error in either U_t or Re_t is about 2 percent at altitudes near 1000 feet, is about 7 percent for all altitudes below 7000 feet, and becomes somewhat greater at 10,000 feet. The relations are not designed for use at altitudes above 10,000 feet. At droplet diameters greater than 2000 microns there is significant droplet flattening. The degree of flattening is dependent upon surface tension and will vary with the substance. Accordingly, the errors are larger and not easily predictable at diameters above 2000 microns.

Expressions that provided quantitative information concerning droplet density, air density, air viscosity, air temperature, and droplet temperature in the calculations are given here as equations (B8) to (B12) (ref. 4) as a matter of reference.

The value of 0.78504 of equation (B8) was based on information available at the time at which this work was done. It differs by a bit more than 1 percent from the value used later in the evaporation calculations, but the difference in the fall rates is inappreciable.

APPENDIX C

CALCULATION OF RATE OF EVAPORATION

Calculation of the rate of evaporation requires a knowledge of the ambient conditions, speed of fall of the droplet, temperature of the droplet, size and composition of the droplet at any time, and the properties of the actual or assumed components of the fuel.

As in all similar work in this field (refs. 1, 5, and 6, e.g.), a stepwise solution was required in view of the complexity of the relations among the many variables even in the case of evaporation of a pure substance.

The general scheme in the present work was as follows. During a single step, occupying a fixed increment of time, the droplet diameter and temperature were held fixed at values roughly average for the interval in question. Terminal speed and Reynolds number essentially average for the interval were calculated as in appendix B.

The Nusselt number of mass transfer was then calculated; the mass-transfer coefficient for each constituent was then obtained from the Nusselt number. The vapor pressure of each constituent was then calculated and used with the proper mass-transfer coefficient and the mole fraction of the constituent to obtain the rate of evaporation of the component (per unit droplet surface area).

When the droplet area and length of the time interval were taken into account, the individual component mass losses were available, hence the total loss for the interval. The change in volume was then computed by using the existing mean droplet density (which changed very slowly, permitting use of this rigorously incorrect procedure), and a new mean diameter for the following step was then obtained from the new volume. The procedure was repeated until either the droplet struck the ground or the total mass loss rate became negligible. The details are now given.

The atmosphere was considered to consist of air having a molecular weight of 28.966 grams per mole; the sea-level pressure was taken as standard (1,013,250 dyne cm^{-2}). Sea-level temperatures were taken as -30° , -15° , . . . , $+30^{\circ}$ C, as indicated in the text and figures. A fixed, standard lapse rate of 0.0019812° C per foot was assumed; the relations among pressure, density, temperature, and altitude were then those of reference 4, with the respective ground temperatures replacing the fixed NACA standard temperature of 15° C.

As noted in appendix B, the effect of variation of air density and temperature (within normal limits below an altitude of 7000 ft) on terminal speeds and Reynolds numbers had been found to be small; the approximation was made that U_t and Re_t were functions only of droplet diameter (eqs. (B4) to (B7)). However, air (hence, droplet) temperatures were of course varied, as was the ambient pressure, in the calculation of vapor pressures and mass-transfer coefficients, in accordance with expressions given below.

Droplet temperature, as indicated in the main text, was taken as equal to ambient to expedite the calculations. This is an unusual simplification and requires justification. Reference 1 indicates that for the much more volatile substance *n*-octane the maximum difference between air and droplet temperatures was 9° C, but this occurred only at an air temperature of 30° C. Evaporation rates of JP-4 droplets are, on the average, an order of magnitude smaller than those of *n*-octane (or gasoline), and it is clear that only infrequently would droplet cooling warrant the refinement of exact droplet temperature calculation. From an operational standpoint, the error at low air temperatures (at which the jettisoning problem is most serious) is vanishingly small.

The more important quantitative relations used in derivations or calculations are given together here; they are followed by explanatory discussion:

$$Nu_m = 2 + 0.55 \overline{Sc}^{1/3} Re_t^{0.5} \quad (C1)$$

$$\overline{Sc}^{-1} = \frac{(\beta_1 + \beta_2 + \beta_3)\rho_a}{3\mu_a} \quad (C2)$$

$$h_{m,i} = \frac{Nu_m}{D_d} T_a^{n-1} P_a^{-1} \beta_{O,i} M_i \left(\frac{NP}{(NT)^{n_R}} \right) \quad (C3)$$

$$\frac{1}{\pi D^2} \frac{dm_i}{d\theta} = h_{m,i} P_i \epsilon_i \quad (C4)$$

$$\beta_{O,i} = 0.0043 \frac{T_O^{3/2}}{P \left(V_1^{1/3} + V_2^{1/3} \right)^2} \left(M_1^{-1} + M_2^{-1} \right)^{1/2} \quad (C5)$$

$$\log_{10} p_i = \frac{-7.7702702(\text{NBP})_i}{T_d^*} + 28.03809 - 7.0274130 \left(\log_{10} T_d^* + \log_{10} \frac{769.7}{(\text{NBP})_i} \right) \quad (\text{C6})$$

$$\frac{T_1}{T_2} = \frac{T_1}{T_2} + C(T_1' - T_1) \quad (\text{C7})$$

(in which any absolute system of temperatures may be used)

$$\frac{dp}{p} = \frac{L_v}{R} \frac{dT}{T^2} \quad (\text{C8})$$

(in which any consistent set of units may be used)

$$L_v = L_{v,0} \left[1 - 0.000667(T^* - 459.7) \right] \quad (\text{C9})$$

$$\log_{10} p = -C_1 \left(\frac{1}{T^*} + 0.001175 \log_{10} T^* \right) + C_2 \quad (\text{C10})$$

The Nusselt number for mass transfer was calculated by using equation (C1), in which \overline{Sc} is a fixed mean Schmidt number.

Use of the exponent 0.5 and fixed coefficient 0.55 represents a computer-speed-biased compromise among conflicting values given in a number of sources (e.g., ref. 7); the resulting Nusselt numbers fit most experimental curves within several percent in the Reynolds number range of interest.

A fixed mean Schmidt number of 3.442 was used in equation (C1). The reciprocal of this number was obtained by multiplying the average diffusion coefficient (at normal temperature and pressure) of the three most volatile components by a representative value of ρ_a/μ_a , as indicated in equation (C2). The (mean) value of ρ_a/μ_a was taken as 6.57 (cgs units).

The mass-transfer coefficients of the individual components were calculated after the determination of Nu_m according to relation (C3).

This expression was obtained in the following manner: The basic relation yielding $h_{m,i}$ is

$$h_{m,i} = \frac{Nu_m}{D_d} \beta_i \frac{M_i}{RT_a} \quad (\text{C11})$$

as in, for example, reference 1.

Although the value of Sc was held fixed in equation (C1), it is desirable to take into account the variation of β_1 in the present expression. The following may be written:

$$\beta_1 = \beta_{0,1} \left(\frac{T_a}{NT} \right)^n \left(\frac{NP}{P_a} \right) \quad (C12)$$

as in reference 1.

When this expression is substituted for β_1 in equation (C11), equation (C3) is obtained. The best choice of the exponent n is suggested to be 1.75 in reference 8 (p. 538).

The individual mass loss rates (per unit area) are then the respective products of $h_{m,1}$, vapor pressure of the component in the absence of other liquids, and mole fraction for the several components as indicated in equation (C4). The product $\rho_{d,1}\epsilon_1$ in equation (C4) represents the partial pressure of the i^{th} component of the mixture assuming Raoult's Law holds.

Calculation of the diffusion coefficients $\beta_{0,i}$ and vapor pressures was accomplished as follows. A mixture of equal volumes of ten petroleum fractions was substituted for JP-4. The successive fractions corresponded to successive portions of an ASTM distillation curve of average JP-4 (ref. 9). For example, component 1 was assigned a boiling point of 639.7°R corresponding to the mean value for the first 10 percent of the distilled fuel. Where required, properties of the components were obtained from reference 10.

The various boiling points, molecular weights, and so forth of the ten components are assembled in table I. It is obvious that three figures, at most, are significant in each instance. The numbers, however, are those used in the calculations and form, moreover, a consistent set.

As checks, various averages and sums were computed. The volume-mean boiling point of these data is 319°F as compared with the 320°F of reference 9 (p. 76). Additional mixture boiling points of these data are (ref. 10, pp. 14-18): mean average, 295°F ($= 319^\circ - 24^\circ \text{F}$); weight average, 310°F ($= 319^\circ - 9^\circ \text{F}$). These compare well with the corresponding numbers 296° and 313°F as cited in reference 9. The weight-mean density of these data is 0.7705, whereas a typical normal-temperature density of JP-4 is 0.773. The mixture chosen would have a characterization factor of about 11.7, which compares well with the range 11.6 to 11.8 given in reference 9 (p. 30).

The agreement between the successive boiling points of JP-4, on the one hand, and the corresponding boiling points of the assumed mixture on the other, together with the correspondence of characterization factors, indicates that JP-4 has been simulated well enough for the present investigation.

In reference 8 (p. 538), the expression (C5) is given, and this was used (although with altered coefficient) to calculate the binary diffusion coefficients. Each characteristic volume (V_1 , e.g.) is the quotient of the molecular weight and the density of the liquid at the boiling point for one of the two substances. (In relation (C5) p is expressed in atmospheres, T_0 in $^{\circ}\text{K}$, and V_1 and V_2 in $\text{cm}^3 \text{ mole}^{-1}$.) In this work V_2 becomes V_a .

The coefficient of equation (C6) was changed from 0.0043 to 0.004215 to force a computed value of 0.0505 for n -octane; 0.0505 is the accepted value for the pair n -octane-air at 0°C and standard pressure.

The expansion factors and molecular weights given in table I are required in the calculation of the characteristic volumes of equation (C5).

The final expression used in the calculation of the vapor pressure p_1 of each component at a given droplet temperature T_d^* is given as equation (C6); the derivation follows immediately. In this relation, p_1 is expressed in atmospheres and the temperatures ($(\text{NBP})_1$ and T_d^*) are in $^{\circ}\text{R}$.

The general scheme is the following. A reference temperature is calculated at which the vapor pressure of the reference substance will be equal to that of the actual substance (component) at the actual (droplet) temperature. This reference temperature is then used in an integrated Clapeyron equation to find the vapor pressure desired.

The Ramsey-Young equation (C7) (semiempirical; ref. 8, p. 294) provides a means of calculation of the reference temperature. Equation (C7) connects two pairs of absolute temperatures (T_1' and T_2' as the one pair and T_1 and T_2 as the other) at which two substances (indicated by subscripts 1 and 2) have identical vapor pressures; the empirical constant C approaches zero for substances of similar chemical nature (e.g., a hydrocarbon series). In this work, C is taken to be exactly zero, and the two boiling points are taken as one of the pairs of temperatures. The simplified Ramsey-Young relation is then that the ratio of the absolute temperatures at which two chemically similar substances have the same vapor pressures equals the ratio of their boiling points. This was

checked against nomographs of reference 6 which yield vapor pressure as a function of temperature for many hydrocarbons. Specific examples involving hydrocarbons having normal boiling points of 100°, 200°, and 374° F at various temperatures ranging from 50° to 360° F indicated that maximum deviations are in the vicinity of 1 percent.

The vapor pressure of the hypothetical reference material at the reference temperature is calculated as follows. The Clausius-Clapeyron relation is given as equation (C8) in which, of course, any consistent set of units may be used. The heat of vaporization of JP-4 decreases from about 165 Btu per pound at 0° F to about 154 at 100° F (ref. 9, p. 128). Accordingly, L_v may be expressed as in equation (C9), where T^* is expressed in °R. Equation (C9) becomes, upon integration,

$$\log_e p = K_1 \left(-\frac{1.30662}{T^*} - 0.000667 \log_e T^* \right) + K_2$$

where p is expressed in units consistent with those of the constants of integration K_1 and K_2 . This is easily alterable to the form given as equation (C10).

The constants C_1 and C_2 were determined by using data from Maxwell's nomograph connecting vapor pressures, temperatures, and boiling points of hydrocarbons. Several simultaneous solutions using two sets of data led to the average values $C_1 = 5980.777$ and $C_2 = 28.03809$ for a reference hydrocarbon having an NBP of 769.7° R, if p is expressed in atmospheres.

If now one writes

$$T_{\text{ref}}^* = T^* \frac{(\text{NBP})_{\text{ref}}}{(\text{NBP})_i} = T^* \frac{769.7}{(\text{NBP})_i} \quad (\text{C13})$$

and replaces the T^* of equation (C10), which is in reality T_{ref}^* , by the expression on the right side of equation (C13), one obtains after some manipulation the desired equation (C6).

Most of the interrelations among the several variables characterizing the size and nature of the droplet are indicated among the symbols (appendix A). In addition, it may be added that the quantity $\alpha_i/m_d = m_i/m_d M_i$ represents the moles of the i^{th} component per unit mass of mixture. This quantity is listed in the last column of table I.

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TABLE I. - PROPERTIES OF COMPONENTS OF ASSUMED MIXTURE

Component	Mean boiling point, °R	769.7 Mean boiling point, nondimensional	Density		Molecular weight, M_i , g/mole	Weight fraction, m_i/m_d , nondimensional	Weight fraction times molecular weight, g/mole	Expansion factor ^a	Moles per unit mass, $(m_i/M_i)/m_d$, mole g ⁻¹
			°API	ρ_i , g/cm ³					
1	639.7	1.203220	77	0.68	96	0.0882544	8.47242	1.095	0.0009193167
2	692.7	1.111159	67	.712	111	.0924075	10.25723	1.130	.0008325000
3	724.2	1.062828	60	.74	120	.0960415	11.52498	1.155	.0008003458
4	749.2	1.027363	55	.76	124	.0986372	12.23101	1.170	.0007954613
5	769.2	1.000650	50	.78	130	.1012330	13.16029	1.180	.0007787154
6	788.2	.976529	48.2	.788	136	.1022713	13.90890	1.195	.0007519949
7	808.7	.951774	46.5	.795	142	.1031798	14.65153	1.207	.0007266183
8	833.7	.923234	44.5	.804	150	.1043478	15.65217	1.225	.0006956520
9	866.2	.888594	42	.816	161	.1059053	17.05075	1.235	.0006577969
10	915.7	.840559	38.8	.83	180	.1077223	19.39001	1.270	.0005984572
Sum				7.705 for 10 cm ³		1.0000001	(\bar{M}) = 136.29929		0.007556859 Total per unit mass

^aRatio of density at room temperature to density at boiling point.

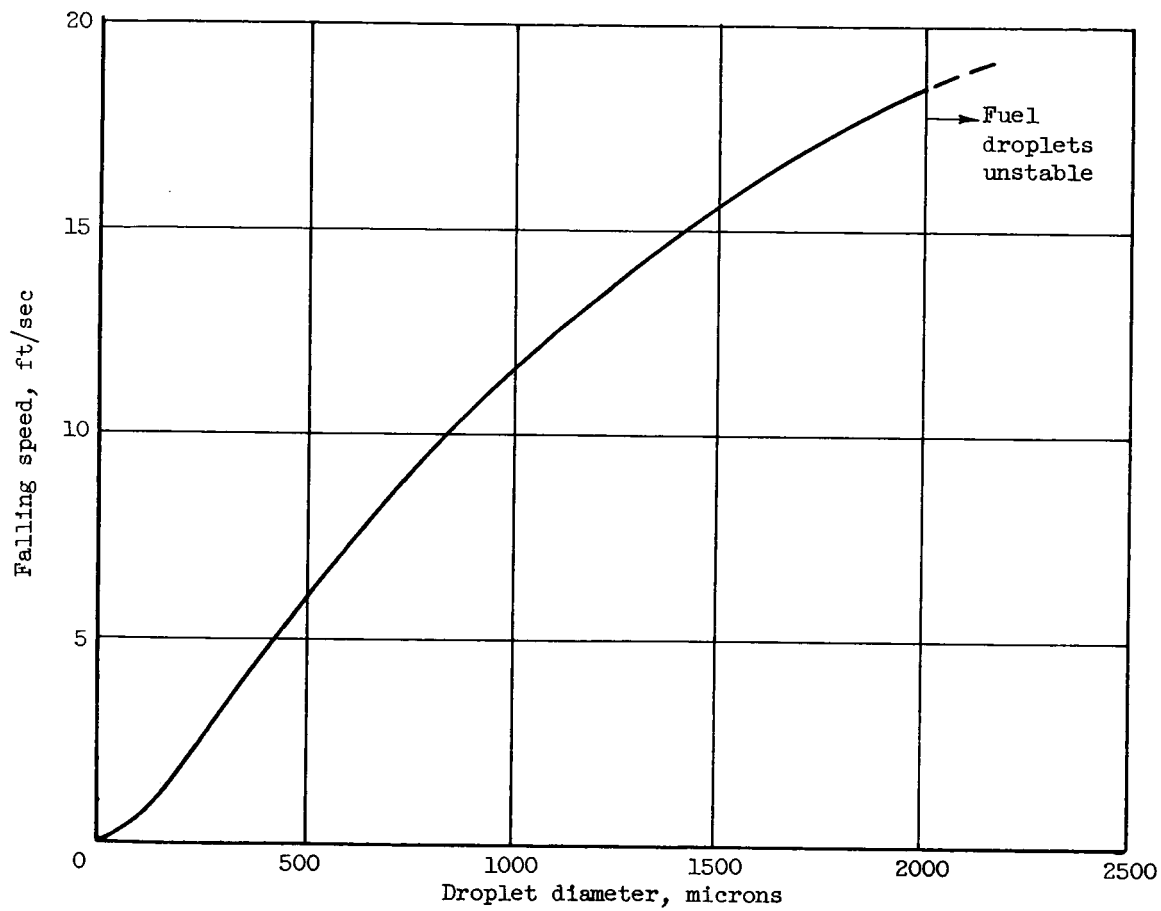
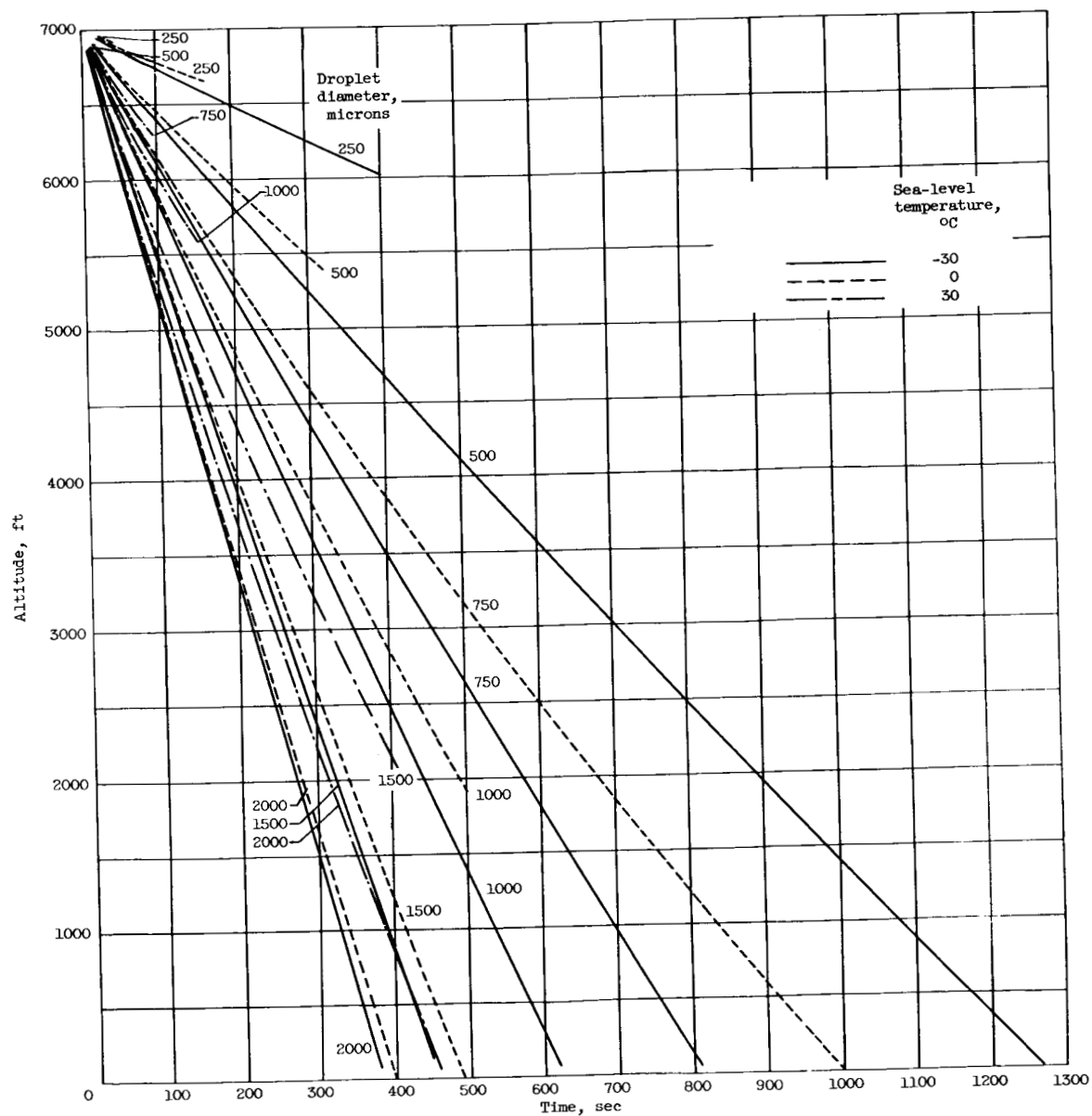
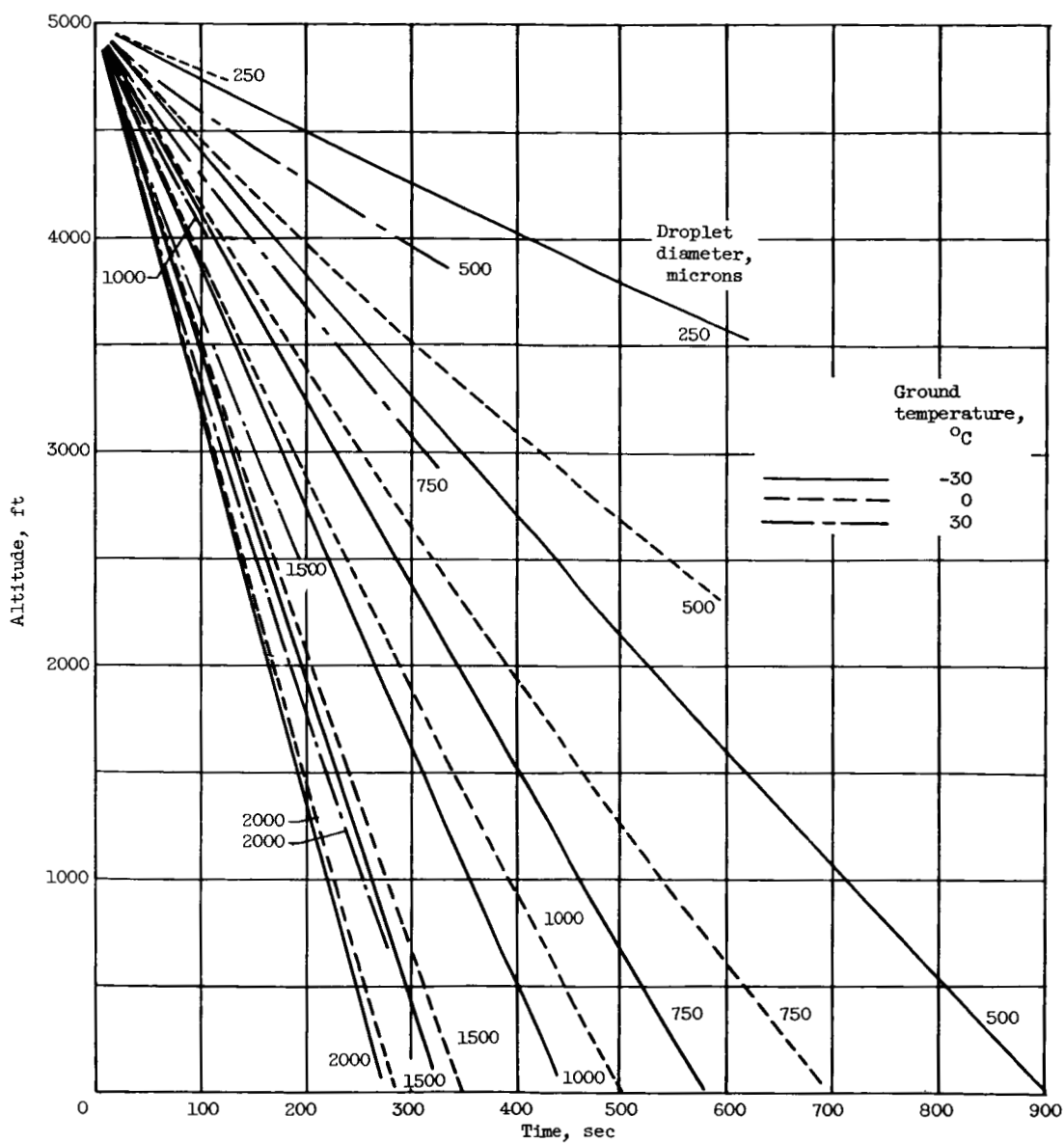


Figure 1. - Terminal falling speed of droplet as function of diameter. (No evaporation during fall.) Altitude, 1000 feet; fuel, JP-4.



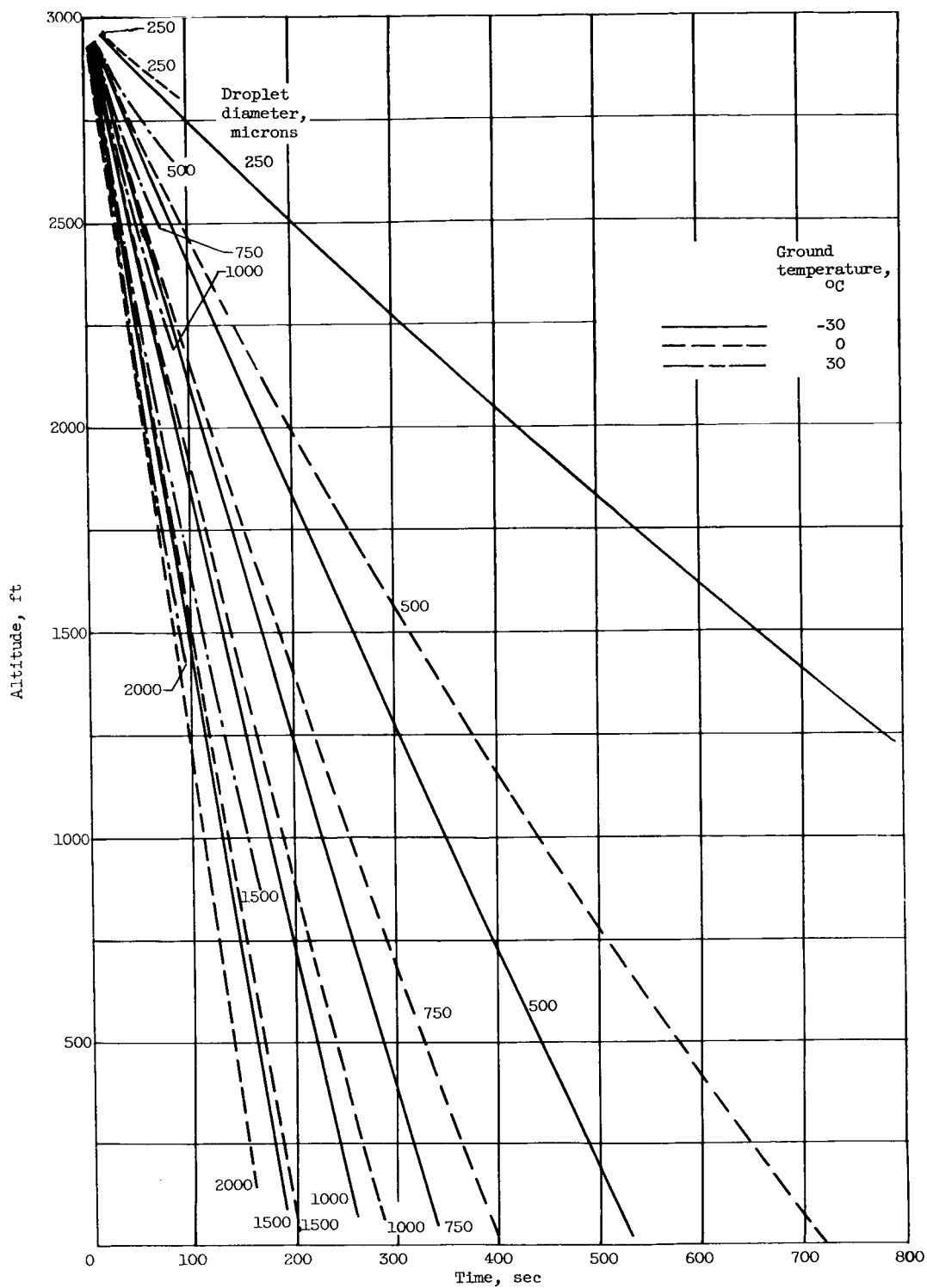
(a) Starting altitude, 7000 feet.

Figure 2. - Droplet altitude as function of time after release for fixed sea-level air temperatures and initial droplet diameters. Fuel, JP-4.



(b) Starting altitude, 5000 feet.

Figure 2. - Continued. Droplet altitude as function of time after release for fixed sea-level air temperatures and initial droplet diameters. Fuel, JP-4.



(c) Starting altitude, 3000 feet.

Figure 2. - Concluded. Droplet altitude as function of time after release for fixed sea-level air temperatures and initial droplet diameters. Fuel, JP-4.

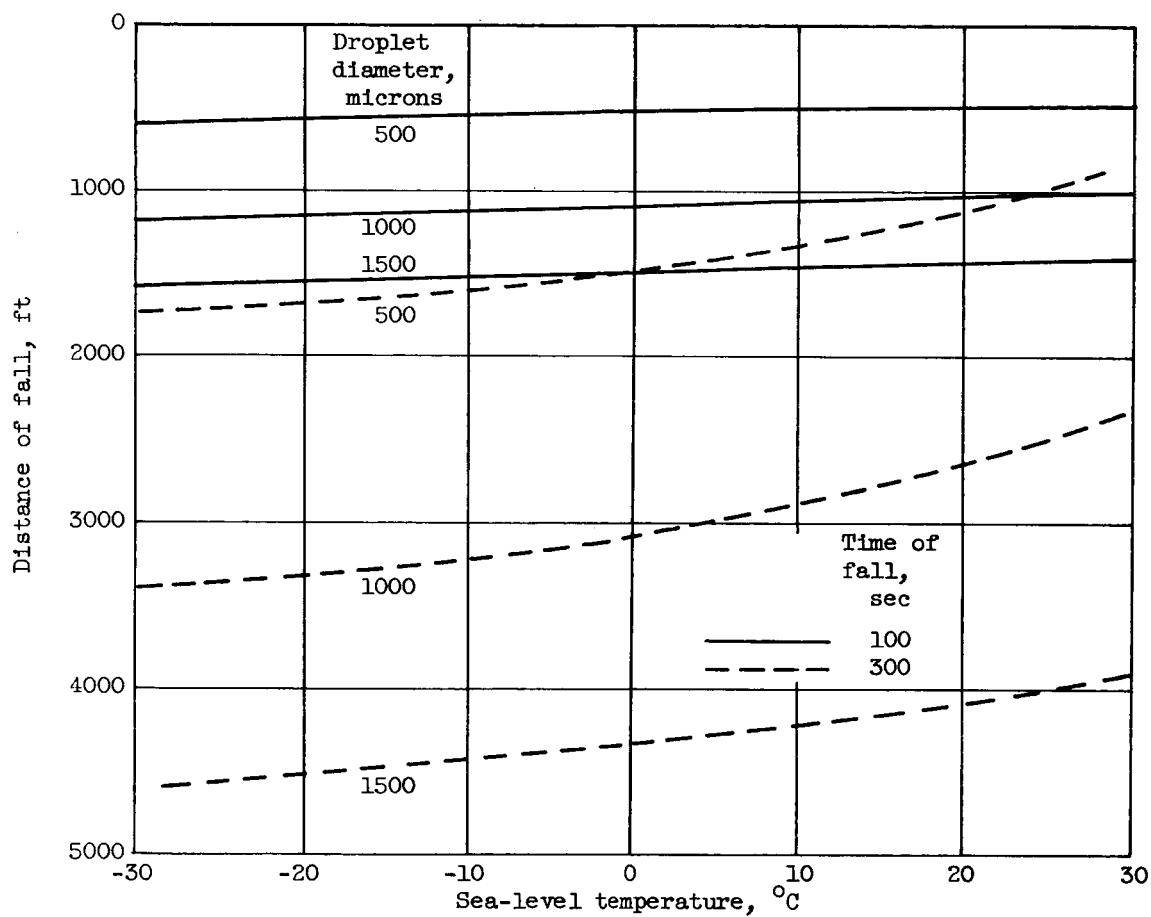
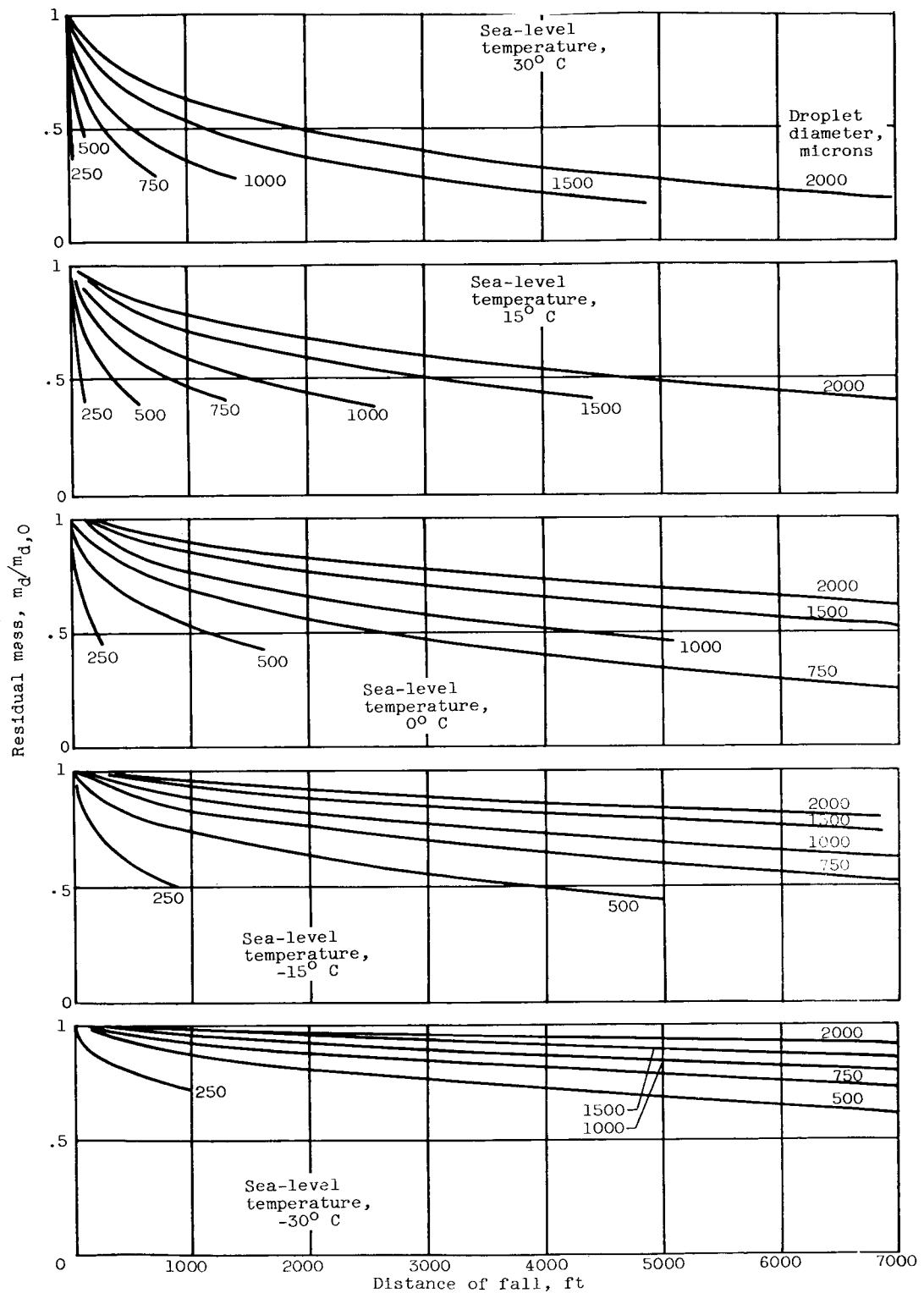


Figure 3. - Distance of fall as function of sea-level air temperature for fixed times after release. Initial altitude, 5000 feet.



(a) Starting altitude, 7000 feet.

Figure 4. - Residual mass as function of distance of fall at fixed sea-level air temperatures. Fuel, JP-4.

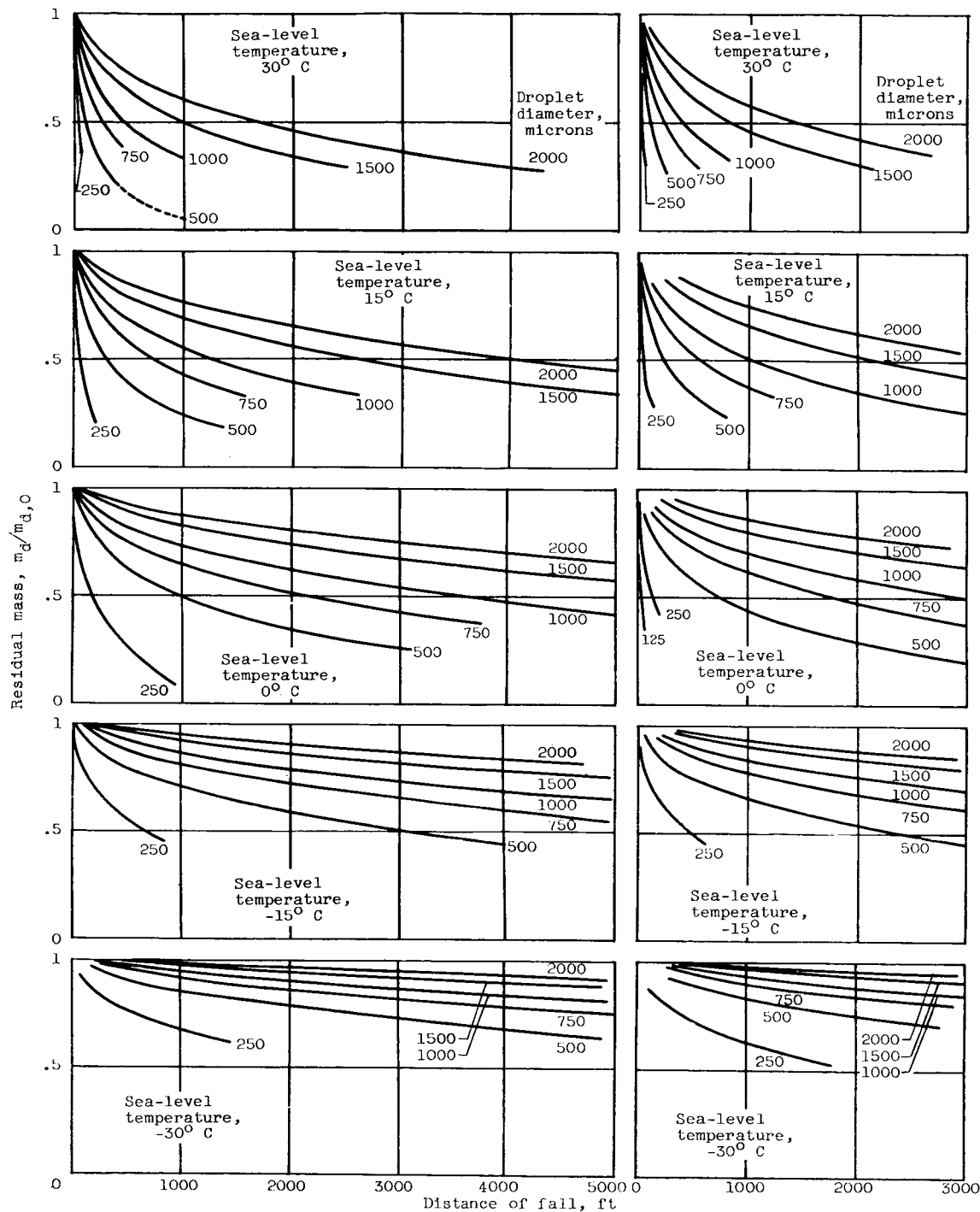


Figure 4. - Concluded. Residual mass as function of distance of fall at fixed sea-level air temperatures. Fuel, JP-4.

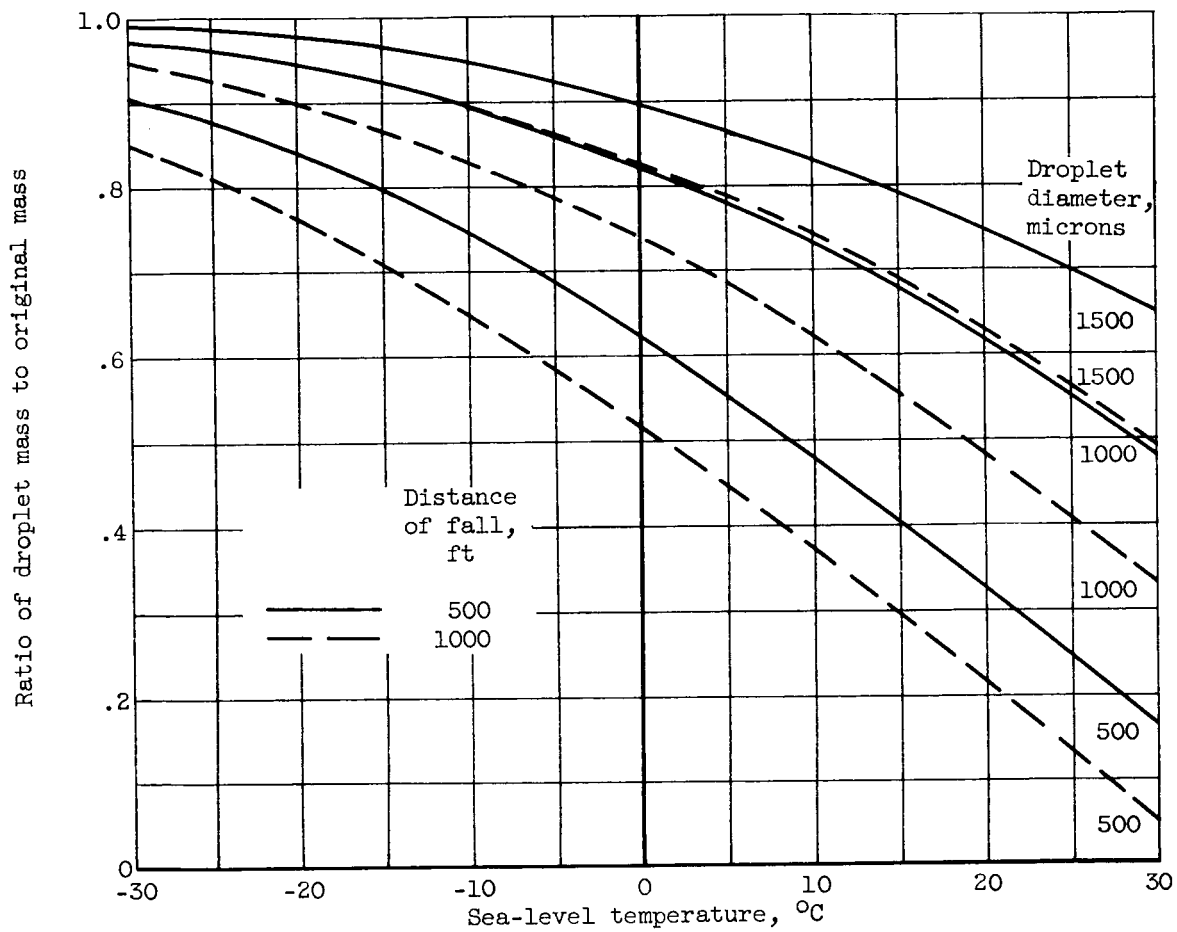


Figure 5. - Effect of air temperature on loss of droplet mass during fall. Starting altitude, 5000 feet; fuel, JP-4.